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ACTIVE NOISE CONTROL WITH MULTIPLE ADAPTIVE FILTER FOR SINGLE COMPONENT IN ACCELERATION

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Abstract. *Vehicle noise is one of the serious problems. Active noise control (ANC) is an effective method for low-frequency noise such as vehicle's engine noise. The purpose of this study is to demonstrate the effectiveness by using ANC in reducing the vehicle engine noise produced during acceleration. In previous studies, tracking the variations in the fundamental frequency resulting from the fluctuation of the engine's rotation during acceleration presented quite a challenge. Therefore, in the present study, sinusoidal waves, consisting of numerous frequencies, are employed as reference signals. Each reference signal is inputted to its respective adaptive filter. In this manner, we attempt to expand the reduction range by utilizing multiple adaptive filters. As a result, we achieve noise reductions of at least 8 dB for acceleration and at least 20 dB for constant-speed driving.*

Keywords: ANC, Engine sound, LMS algorithm, Sound of acceleration, Reference signal

1. Introduction.

Improvement in the combustion efficiency of the engine of a vehicle can be realized by increasing the quantity of the inflow air; however, this is accompanied by an increase in the engine noise. Active noise control (ANC) is an effective solution to the problem of this relationship. ANC is a method for reducing low-frequency noise that is difficult to reduce using conventional passive-reduction methods focusing on the characteristic of insulation, proofing, and dampening materials [1]. Furthermore, ANC is suitable for controlling of engine noise, or other booming noises, as the equipment used for it does not require a large space for installation [2,6]. In previous studies, we performed experiments on a reference signal for both the fundamental frequency and its harmonic, calculated from the engine pulse and focused on partial structures [7]. However, it was difficult to track the changes in the fundamental frequency, because this frequency depends on the rotational fluctuations of the engine during acceleration [5]. Thus, the aim of this investigation was to use ANC to realize noise control during acceleration.

Methods for improving the tracking performance of high-speed fluctuations include increasing the speed of the control with high-performance devices, and improving its precision to estimate the most suitable value of the step size parameter for the adaptive filter coefficient.

In this study, we adopted a different approach by employing sinusoidal waves of numerous frequencies as reference signals. Each reference signal was input to its respective adaptive filter. In this manner, we attempted to expand the reduction range by utilizing multiple adaptive filters. Finally, we investigated the optimum frequency interval of the reference signal for controlling the engine intake sound.

2. Control Algorithm.

The algorithms employed in our experiments are presented in this section. We use feedforward control with a least mean square (LMS) algorithm. The LMS algorithm utilizes the method of steepest descent and is highly useful, as it allows control in real time using limited hardware.

2.1. Filtered-x LMS algorithm.

The most popular adaptive algorithm used for ANC applications is the filtered-x least mean square (FxLMS) algorithm which is a modified version of the LMS algorithm [3,4]. LMS does not take secondary path effects into account. Therefore, a precise anti-noise signal cannot be generated using LMS. The FxLMS algorithm is a method that can compensate for the effects of the secondary path in ANC applications.

Consider the block diagram of a feedforward ANC using the FxLMS algorithm shown in Figure 1. The adaptive filter $W(n)$ (with filter length N) is then expressed by Equation (1), where μ is the convergence coefficient (i.e., the step size parameter). In the figure, $x(n)$ is the reference signal, $y(n)$ is the control signal, $d(n)$ is the desired signal, $e(n)$ is error signal, G is the secondary path (between the sensor and actuator), $\widehat{G}$ is the model of the secondary path, and $r(n)$ is the filtered reference signal.

$$W(n+1) = W(n) + \mu(n)e(n)r(n) \tag{1}$$

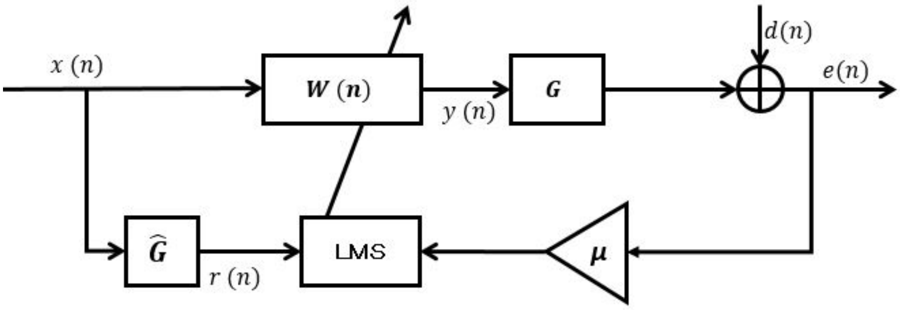

Figure 1. Block diagram of FxLMS algorithm

2.2. Harmonic filtered-x LMS algorithm.

Improvements in the silencing ability of the ANC can be achieved by using multiple reference signals. However, this increases both the complexity and the cost of a system. The use of a harmonic FxLMS (HFxLMS) algorithm, which focuses on the harmonic structure of engine noise, is one approach to solving these problems. HFxLMS algorithm provides control by using the basic frequency along with its higher-order harmonic components determined from the period of the engine pulse signal generated on the digital signal processor (DSP). It can reduce the number of sensors and provide stable control, because it adopts an engine pulse signal for reference. Furthermore, it provides more stability to the control system by updating the multiple adaptive filters and subsequently setting the most suitable convergence coefficient for the component of each order. The HFxLMS algorithm effectively controls noise with a harmonic structure, such as that produced by a vehicle engine or a ship's engine.

Figure 2 shows the block diagram of the HFxLMS algorithm used in this study. The control signal, $y(n)$, is expressed by Equation (2). Its order is indicated by M.

$$y(n) = W_1(n)x_1(n-i) + \cdots + W_M(n)x_M(n-i) \tag{2}$$

The error signal, $e(n)$, is expressed by Equation (3).

$$e(n) = d(n) + \sum_{i=0}^{N-1} G(i)y(n-i) \tag{3}$$

The adaptive filter W_M (with filter length N) that reduces the error signal is then expressed by Equation (4).

$$W_M(n+1) = W_M(n) + \mu_M(n)e(n)\sum_{j=0}^{N-1}\widehat{G}(j)X_M(n-c-j) \tag{4}$$

However, it is challenging to track the variations in the fundamental frequency resulting from the fluctuation of the engine's rotation during acceleration using this algorithm.

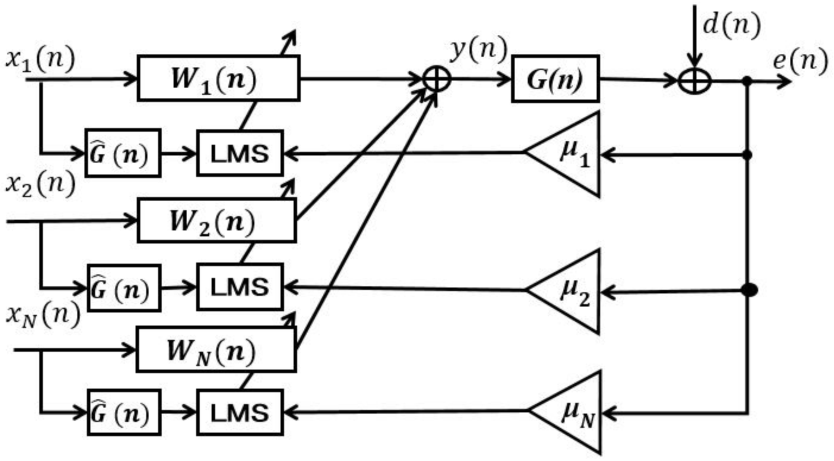

FIGURE 2. Block diagram of HFxLMS algorithm

2.3. **Proposed method.** Parallel active control is a technique specific to reduce single order component of engine noise in acceleration. In this paper, we focus only on the second-order component of the engine's noise, because this component has the highest sound pressure. This method can also control, simultaneously, some components of other orders. Sinusoidal signals that consist of numerous frequencies close to the target frequency, which are determined from the period of the engine pulse, are employed as reference signals. Each reference signal is input to its respective adaptive filter. In this manner, we attempt to expand the reduction range by utilizing multiple adaptive filters. In addition, the update type of adaptive filter W_M is similar to that of the HFxLMS algorithm given in Equation (4). If we let the sinusoidal signals correspond to the components of each order of the reference signal, we can control not only the first-order component but also some components of other orders. The number of reference signals that can be controlled depends on the calculated processing performance of the device generating the control signal.

3. **Experiment.** We performed a simulated space control experiment using a motorcycle engine system model. We used engine intake noise for the simulations that we recorded from an actual vehicle. Figure 3 shows the system used in the experiment. The control point was assumed to be located at an inlet port on the front left side of the body of the vehicle, and control was provided with a fixed error sensor (Ono Sokki, MI-1432) 7 cm away from the body. We installed a control speaker (Kenwood, KFC-RS170) to reduce the engine intake noise incident upon the cleaner box. We used five reference signals and determined the control object as the secondary component, as the sound pressure of this component becomes high during rapid acceleration. Two cases were chosen for the frequency interval between the reference signals, 0.1-1 Hz, in order to investigate the optimum noise reduction for these two simplified cases.

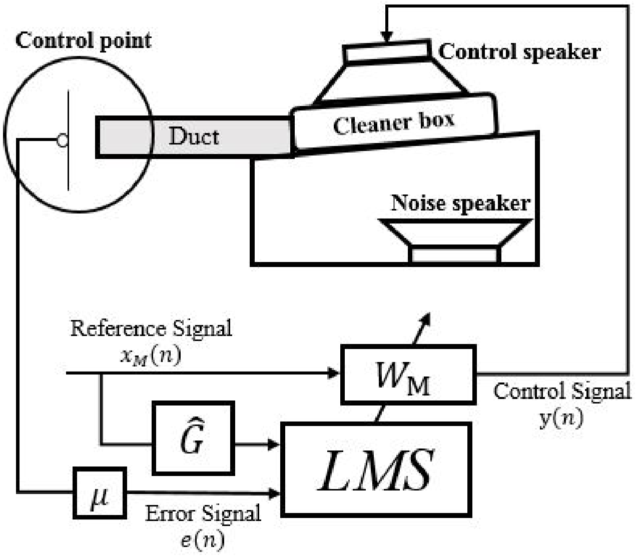

FIGURE 3. System used in experiment

4. **Results and Discussion.** Figures 4-6 show the spectrograms of the engine intake sound recorded at the control point. Figure 4 shows the resulting noise when the ANC control was not utilized. Figures 5 and 6 show the effects of control for second order component and we can see the reduction in that point. Figure 5 shows the results of control by the HFxLMS algorithm (left) and the proposed method (right). Figure 5 confirmed also that the proposed method performed better than the conventional technique because the effectiveness of the proposed method (−22 dB) is better than HFxLMS algorithm (−5 dB) at acceleration. And both controls have close effect at constant-speed driving. Figure 6 shows that the frequency interval of 0.1 Hz had the larger noise reduction of the two cases chosen.

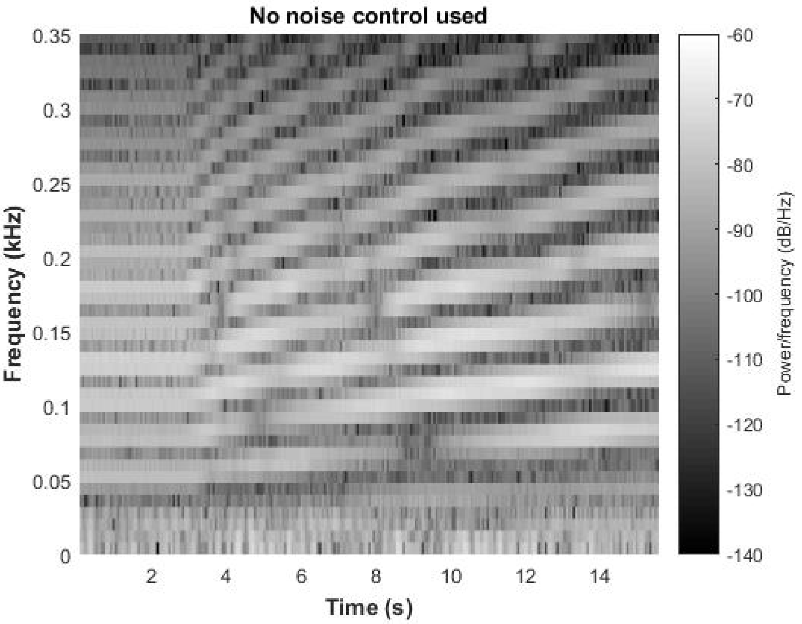

FIGURE 4. No noise control used

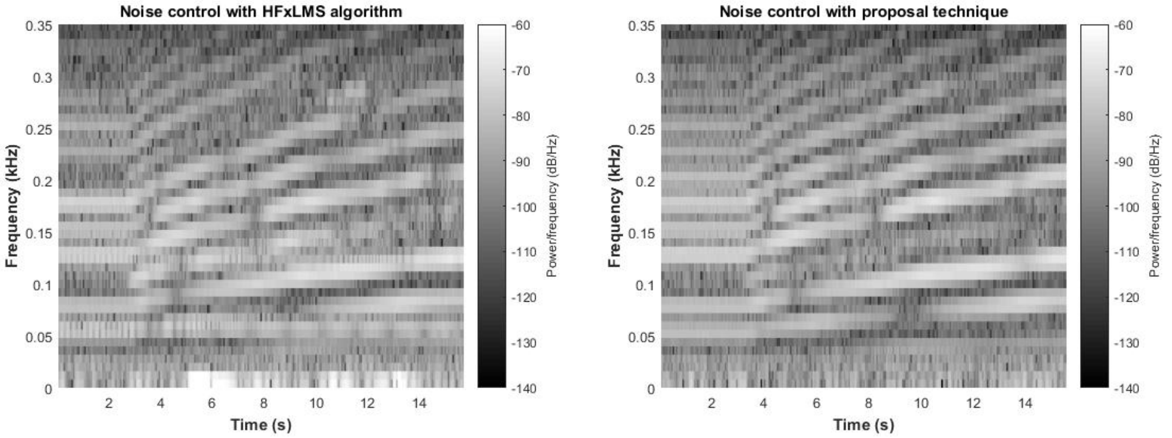

Figure 5. Noise control with HFxLMS algorithm (left) and proposed method (right)

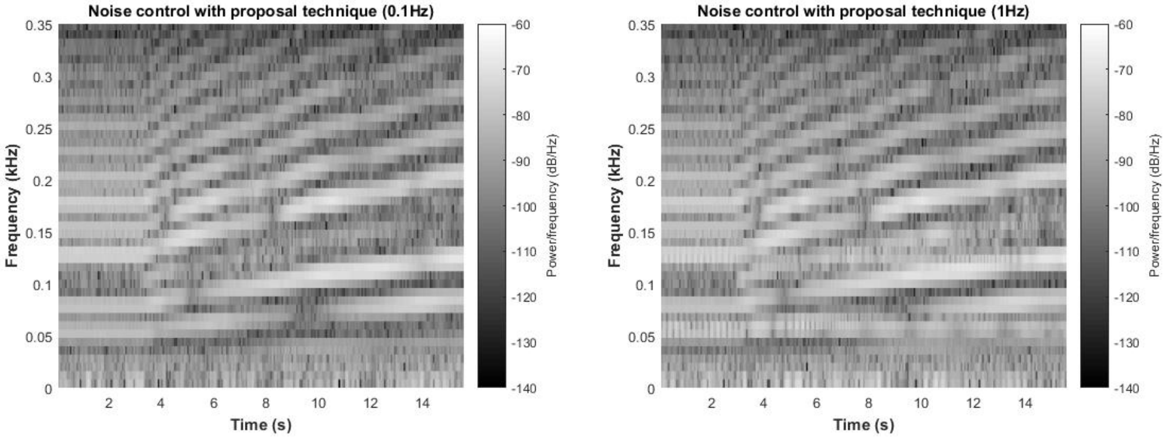

Figure 6. The comparing appropriate control signal's frequency intervals (0.1 Hz (left) and 1 Hz (right))

5. **Conclusions.** We examined the effects of using multiple reference signals to control a single-order component of engine noise, and we compared the proposed method with a previous method employed in ambient conditions. The amount of reduction is 20 dB, much more than the reduction 5 dB by the conventional control method. Our experimental results confirmed that the proposed method worked as expected without resulting in aggravation bands. These results indicated that noise reduction was improved for engine noise fluctuations by employing parallel active control.

In future work, we will use simulation to examine the correlation between acceleration and the intervals of the reference signal frequencies to realize the control of rapidly fluctuating engine noise, and apply the proposed control method to an actual vehicle.

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